REPORT No. 454

PHOTOMICROGRAPHIC STUDIES OF FUEL SPRAYS

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SUMMARY

A large number of photomicrographs of fuel sprays were taken for the purpose of studying the spray structure and the process of spray formation. They were taken at magnifying powers of 2.5, 3.25, and 10, using a spark discharge of very short duration for illumination. Several types and sizes of nozzles were investigated, different liquids were used, and a wide range of injection pressures was employed. The sprays were photographed as they were injected into a glass-walled chamber in which the air density was varied from 14 atmospheres to 0.0013 atmosphere.

Within the range investigated, the photomicrographs support the theory advanced by Dr. R. A. Castleman, jr., to explain the atomization of liquid fuels in carburetors and in injected sprays. With injected sprays, the fuel leaves the nozzle as an unbroken column, is ruffled, and then torn into small, irregular ligaments by the action of the air. The ligaments are then quickly drawn up into drops by the surface tension of the fuel. Turbulent fuel flow accelerates the disintegration of the fuel jet by ruffling its surface close to the orifice, but has relatively small disintegrating power in itself. When other factors are kept constant the degree of disintegration of the jet increases with the distance from the nozzle, the air density, the fuel velocity, or the fuel turbulence, but decreases with an increase of fuel viscosity, surface tension, or nozzle orifice diameter.

INTRODUCTION

More rapid and uniform mixing of the fuel and air in the combustion chambers of fuel-injection engines is essential if the combustion process is to be controlled and higher specific outputs obtained. Accordingly, many experiments have been made to determine the general shape, the rate of growth, the final drop size, and the fuel distribution of sprays from various types of nozzles. However, the study of the manner in which the fuel is divided into the millions of small drops which constitute a fuel spray has hitherto been handicapped by a scarcity of direct experimental evidence. Some investigators have discussed the process of spray formation with particular emphasis on vibrations and turbulent flow within the nozzle. (See references 1 and 2.) Others have been most interested in the effects of the forces which result from the relative motion between the fuel and the air. (See references 3, 4, 5, and 6.)

The investigation described in this report was made to study the formation of fuel sprays by means of instantaneous photomicrographs, and to determine the effect of various design and operating factors on the characteristics of the sprays. The experiments were conducted during the early part of 1932 by the National Advisory Committee for Aeronautics at Langley Field, Va.

APPARATUS AND TEST PROCEDURE

A microscope with camera attachment was used to take photomicrographs at a magnifying power of 10 and a large camera with a short focus lens was used for magnifications of 2.5 and 3.25.

The illumination for photographing the sprays was supplied by a spark from the electrical circuit shown in

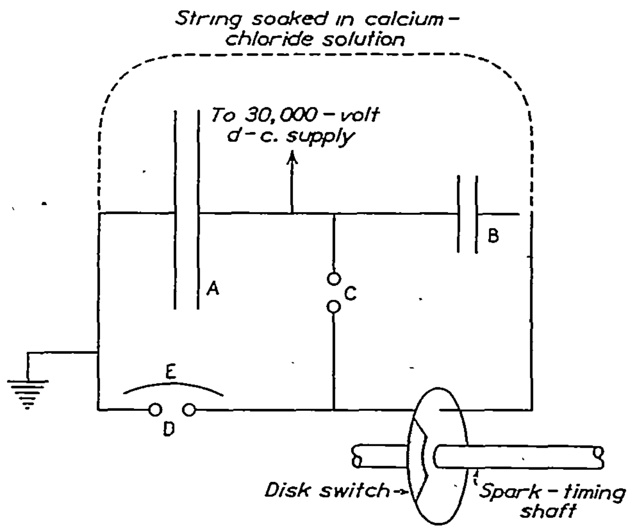


FIGURE 1.—Circuit used to produce illuminating sparks of short duration
A. Main condenser.
B. Auxiliary condenser.
C. Auxiliary spark gap.
D. Illuminating spark gap.
E. Reflector.

Figure 1. The principle of this circuit is as follows: The condensers A and B are charged to a high potential by a transformer and a rectifying tube. When the switch controlling the discharge is closed, the small condenser B discharges across the auxiliary spark

gap C, ionizing the air in the gap and greatly lowering its resistance. Condenser A then discharges across both gaps C and D; the light from gap D is used to photograph the spray, that from gap C being shielded from the camera lens. The duration of the illuminating discharge in circuits of this type is of the order of 10^{-7} second, provided that the resistance of the connecting wires is low. (See reference 7.) In this case, the capacities of the condensers A and B were about 0.01 and 0.001 microfarad, respectively. They were charged to about 30,000 volts and the connecting copper wires were about 0.16 inch in diameter and as short as practicable.

When taking photomicrographs, the spark gap is mounted in front of a parabolic reflector, and the reflector, spray nozzle, and microscope are placed in line so that the photomicrographs are silhouettes. A glass tube was slipped over the spark-gap points, to confine the spark discharge to a relatively narrow path.

The nozzles were used in an automatic injection valve and also as open nozzles. Figure 2 shows a sketch of the injection valve and an enlarged view of a nozzle assembled in the valve. The injection valve was operated by the common-rail fuel-injection system of the N. A. C. A. spray photographic apparatus. (Reference 8.) Synchronization of the spark with the spray from the valve was accomplished by a rotary disk switch on the shaft with the cams that control the injection. The spark could be made to occur at any desired stage in the development of the spray by changing the phasing of the disk switch with respect to the cam shaft. The sprays from the open nozzles were continuous, the fuel being supplied from a reservoir arranged to maintain a constant pressure for several seconds. In this case the timing of the spark was manually controlled. It has been shown by Rothrock in reference 8 that with the common-rail injection system used there are pronounced fluctuations in the instantaneous pressures at the nozzle during the injection period. Therefore, in order that the data might be strictly comparable, continuous sprays from open nozzles were used whenever possible.

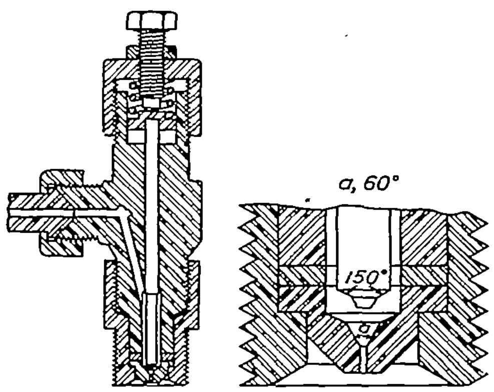


FIGURE 2.—Sketch of automatic injection valve, and enlarged view of nozzle assembled in valve

For experiments at other than atmospheric air density, the sprays were injected into a glass-walled chamber in which the air density could be raised by admitting compressed air from an air bottle or lowered by exhausting the chamber with a vacuum pump.

Except where otherwise noted, the fuel used in the tests was a Diesel fuel oil having, at atmospheric pressure and a temperature of 22° C., a viscosity of 0.022 poise, and a specific gravity of 0.837.

RESULTS AND DISCUSSION

The fact that the photomicrographs are silhouettes must be kept in mind while studying them, because frequently the core of the spray was the only part dense enough to register on the films. Most of the minute drops in the envelope of the spray surrounding the core could not be photographed. At high injection pressures or high air densities the surrounding cloud of drops became so dense that all details were obscured. Therefore, in order to study the process of fuel spray formation to the best advantage, the majority of the photomicrographs were taken at low injection pressures and low air densities. As the conditions were altered progressively until engine conditions were approached, the changes in the spray were carefully studied, and from these observations there have been drawn a number of general conclusions about the formation of fuel sprays.

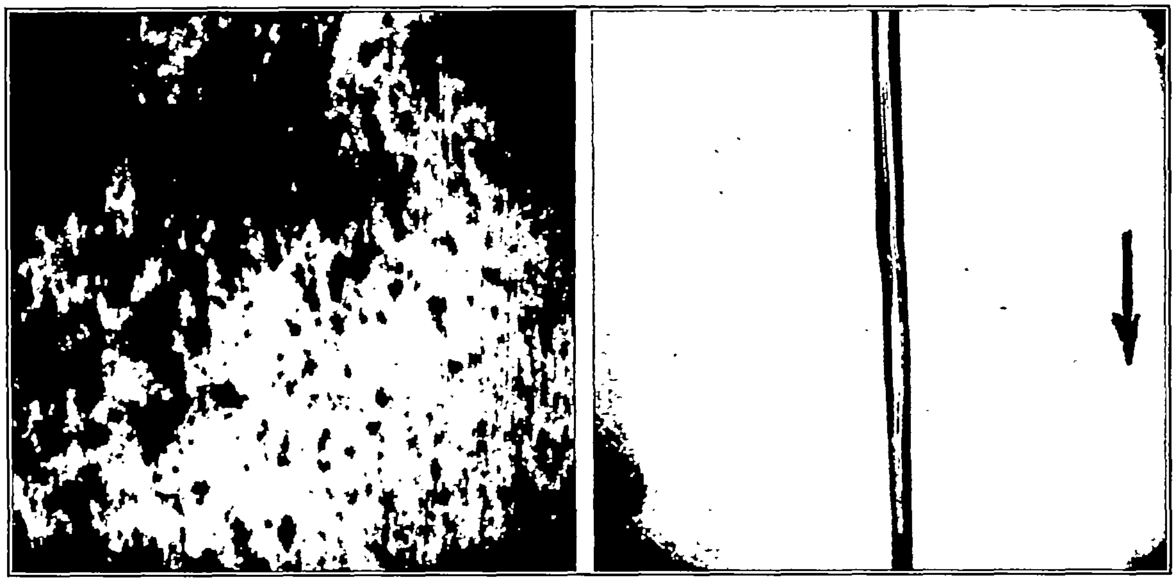
A certain amount of discretion had to be used in selecting representative photomicrographs for illustration. Variations and irregularities, probably caused by fluctuations in the flow through the nozzle, were often present in the fuel jets. Only a relatively small portion of the jet could be photographed, and it sometimes happened that one of these irregularities was in front of the lens when the illuminating spark occurred. Therefore, several photomicrographs were always taken at each test condition, and pictures representative of the general trend were selected. The conclusions presented in this report are based on the study of about 2,800 fuel-spray photomicrographs.

TERMINOLOGY

Many different terms have been used by various investigators in describing the process by which liquid fuel is transformed into fuel sprays. "Jet disintegration", "disruption", "collapse", "decay", and "break-up" have been used, as well as the word "atomization." In this report, the recommendations of Castleman (reference 5) concerning the terminology of fuel-spray formation have been adopted whenever possible. He proposed that the word "atomization" be limited to the last stage of the process, during which the fuel particles attain their final size and form, and that the word "disintegration" be used in connection with that part of the process preceding atomization. The term "dispersion" has quite generally been accepted as denoting the ratio of spray volume to fuel volume. In this investigation, dispersion was estimated qualitatively from the photomicrographs.

DIFFERENCES BETWEEN CONTINUOUS AND INTERMITTENT SPRAYS

As has been mentioned, both continuous sprays from open nozzles and intermittent sprays from an automatic injection valve were photographed. The first portions of sprays from the valve were considerably more dispersed than the later portions; however, when the sprays were fully developed, their appearance was the same as that of continuous sprays. The difference in dispersion between the early and late portions of a spray from the valve was most noticeable when the injection occurred in a vacuum, where the restricting influence of the air was much reduced. As the air density was increased, this difference in dispersion decreased until at high air densities it was relatively slight. This initial dispersion effect is shown quite strikingly by Figure 3, which shows two stages in the development of similar intermittent sprays injected into a vacuum. The first part of the spray is dispersed very greatly, although the individual drops are relatively large. However, 0.002 second after the start the jet appears as an unbroken column. The general appearance of the first and later portions of intermittent sprays injected into air at atmospheric density is shown by Figure 4. As the dispersion of the early part of the spray is most apparent at low air densities when the air has the least restricting effect, it seems probable that the flow conditions at the start of injection are such as to produce considerable turbulence. The momentary throttling as the valve stem leaves its seat and the sudden surge when the fuel under pressure is released contribute to this turbulence. With the exception of Figures 3 and 4, all photomicrographs of sprays from an injection valve, shown in this report, were made when the spray was fully developed.



(a) At start of spray. (b) 0.002 second after start of spray.

FIGURE 3.—Two stages of similar intermittent sprays in a vacuum, × 10. Injection pressure, 2,000 pounds per square inch; orifice diameter, 0.014 inch; air density, 0.0026 atmosphere (pressure =2 mm Hg, absolute); distance from nozzle, 3 inches

THEORIES OF SPRAY FORMATION

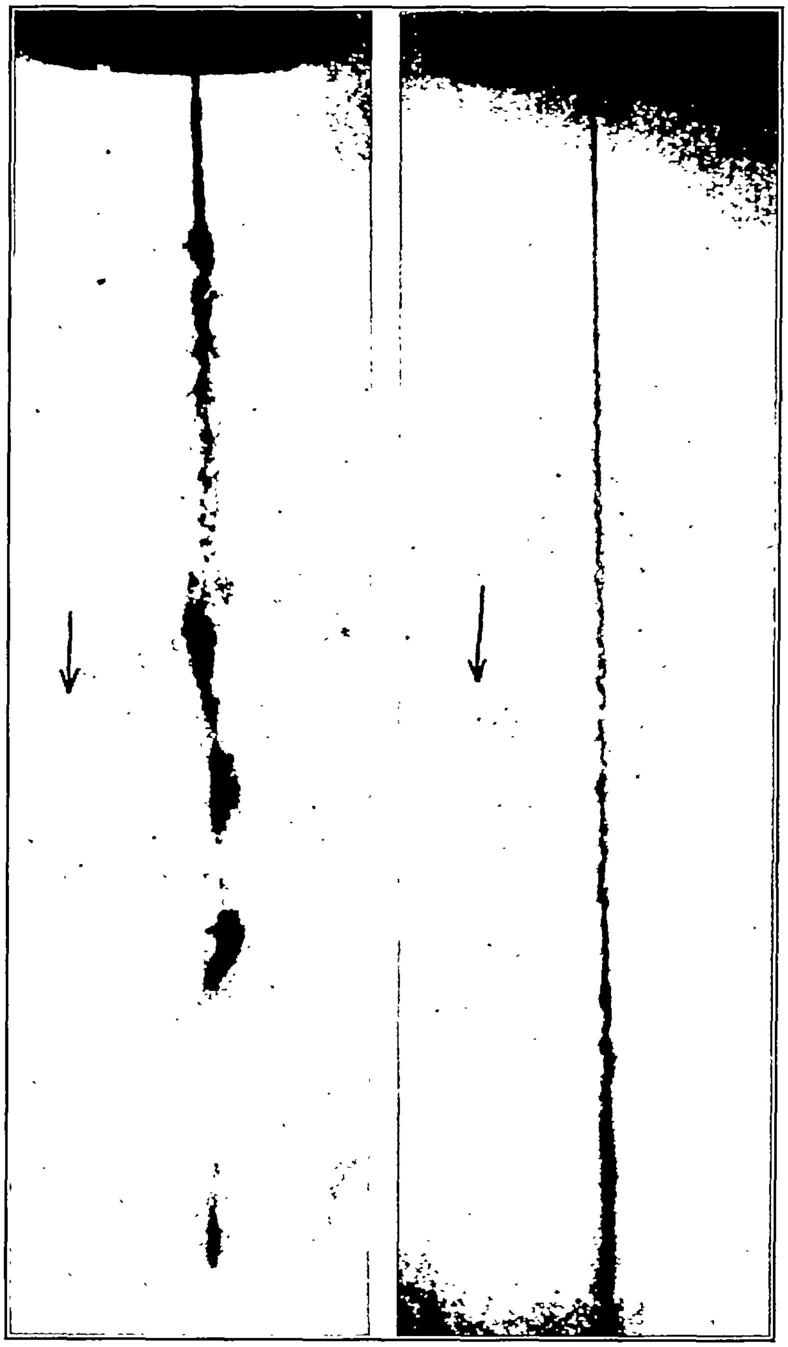
Among recent works on the phenomena of spray formation, the contributions of Haenlein, Castleman, and Schweitzer are the most directly related to the work that has been done at this laboratory.

Haenlein (reference 3) took spark photographs of jets of liquids having a wide range of physical properties and obtained very definite information concerning the nature of the disintegration of a liquid jet up to injection velocities of about 230 feet per second. He described four characteristic disintegration phenomena, which are dependent upon the velocity of injection: (1) Drop formation accomplished solely by the surface tension of the liquid; (2) drop formation where the surface tension is reenforced by air action; (3) wave formation by the air; (4) sudden and complete disintegration of the jet. No explanation was offered for the last phenomenon.

In references 4 and 5, Castleman has expressed a very reasonable explanation of the atomization of liquids. He says, in reference 4:

> The actual process of atomization in an air stream seems rather simple: A portion of the large mass is caught up (say, at a point where its surface is ruffled) by the air stream and, being anchored at the other end, is drawn out into a fine ligament. This ligament is quickly cut off by the rapid growth of a dent in its surface, and the detached mass, being quite small, is swiftly drawn up into a spherical drop. (A quite similar phenomenon occurs when a large drop is detached from a tube.

The chief difference is that the ligament connecting the small drop to the main mass is much finer than that connecting the large drop to the liquid in the tube, and, hence, the time of detachment is enormously less.) The higher the air speed, the finer the ligaments, the shorter their lives, and the smaller the drops formed, within the limits discussed above.



At start of spray. 0.002 second after start of spray.

FIGURE 4.—Two stages of similar intermittent sprays in the atmosphere, × 2.5. Injection pressure, 1,500 pounds per square inch; orifice diameter, 0.008 inch; air density, 1 atmosphere

He also compares airless injection of fuel to air-stream atomization, and concludes that the atomization process is the same in each case, the formation of ligaments being controlled by the relative velocity between the air and the fuel.

Schweitzer discusses the mechanism of jet disintegration in reference 2. He emphasizes the fact that rotationally symmetric disturbances and wavelike disturbances caused by the air can not possibly cause such extremely fine atomization as occurs in ordinary fuel injection, and gives particular attention to the influence of turbulent flow in the nozzle. Experiments are cited in which fuel was injected into a vacuum, and a distinct dispersion was noted at Reynolds Numbers of about 3,500 and above.

TYPES OF JET DISINTEGRATION

The forms of jet disintegration analyzed by Haenlein, caused by rotationally symmetric and wavelike disturbances, are illustrated in Figure 5. In photograph (a) of this figure the jet velocity is so low that the air plays no part, and the fuel column is separated into drops solely by the forces of surface tension. The beginning of enlargements and contractions in the stream is visible at some distance above the point of jet collapse. These inequalities in the fuel column increase slowly at first, then quite rapidly until the column is broken into elongated fragments. These fragments as they are falling through the air continue to be acted upon by surface tension. They therefore shorten themselves and, after a series of oscillations in which they become alternately elongated and flattened, settle down in the form of spherical drops.

In Figure 5(b), which was taken at a higher magnifying power than 5(a), the jet velocity has been increased until the aerodynamic forces also play a part in the disintegration of the jet. The action of the air on the fuel column may be similar to that of the wind on the surface of a body of water. If the relative velocity between the liquid and the layer of air close to its surface increases at the wave crests and decreases in the troughs, the result will be a decrease in pressure at the crests and an increase in pressure at the troughs. These pressure differences will increase the amplitude of the waves, and, in the case of the fuel jet accelerate its disintegration. (See reference 3.)

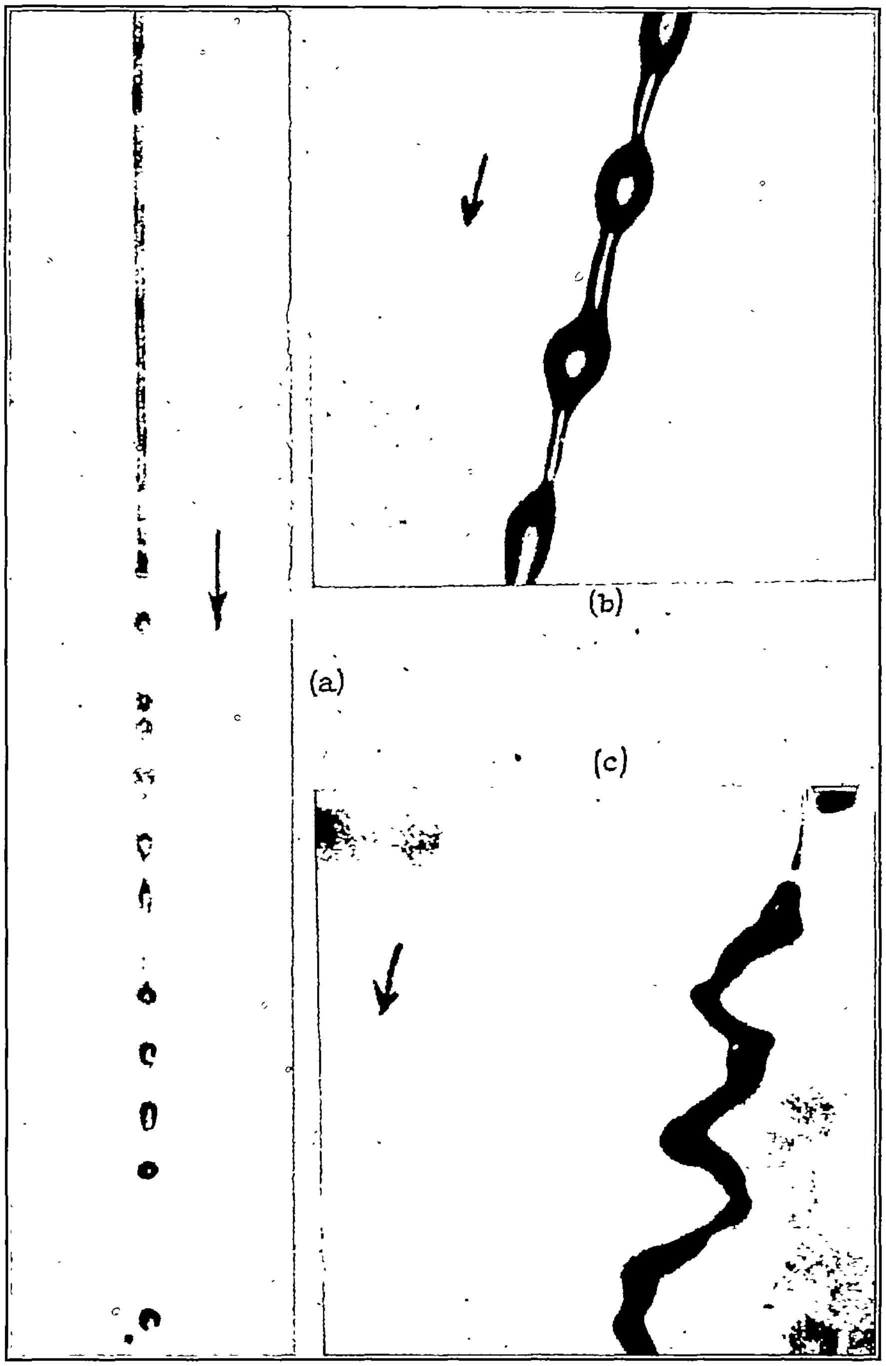


FIGURE 5.—Types of jet disintegration. Orifice diameter, 0.020 inch; air density, 1 atmosphere

(a) Rotationally symmetric disturbances without air influence, × 3.25. Injection pressure less than 10 pounds per square inch.
(b) Rotationally symmetric disturbances with air influence, × 10. Injection pressure, 50 pounds per square inch.
(c) Wave formation, × 10. Injection pressure, 100 pounds per square inch.

In Figure 5(c) the jet velocity is still greater, and waves have been formed in addition to the rotationally symmetric disturbances. These waves are also the result of aerodynamic forces, and at the higher velocities they develop more rapidly than do the rotationally symmetric disturbances so that the jet is broken into many irregular parts.

LIGAMENT FORMATION

The formation of ligaments and their collapse into drops are shown in Figure 6. Virtually all photographs, except those at very low or very high pressures, show such ligaments. At very low pressures the relative velocity of the fuel and air is not sufficient for ligament formation, and at very high pressures the velocity is so high and the ligaments so small and so obscured by the fuel particles in the spray envelope that they are not distinguishable. The collapse of the ligaments is seen to be very similar to the collapse of a larger column, as described in connection with Figure 5.

The similarity between the photomicrographs of Figure 6 and the photographs made by Scheubel of air-stream atomization in a model carburetor (reference 9) indicates that the two methods of atomizing fuel are fundamentally the same.

EFFECT OF TURBULENT FUEL FLOW

The question of fuel turbulence is associated both with nozzle conditions and with Reynolds Number as determined by the injection velocity, the orifice diameter, and the kinematic viscosity of the fuel. If the Reynolds Number is below a certain critical value, any turbulence caused by nozzle irregularities will tend to damp out, but if it is above the critical value, an initial disturbance will persist. From experiments with fluid flow in long, uniform tubes, this critical value has been determined to be about 2,300. As the ratio of the length to the diameter of the nozzle bores was usually 2.5 or less, the use of Reynolds Numbers to determine whether the flow was turbulent or not is somewhat questionable. However, the appearance of fuel jets injected into an evacuated chamber, where the influence of air forces must be negligible, indicates that the Reynolds Number criterion may be applied in most cases.

Figures 7 and 8 show a series of fuel jets in vacuum, for which the Reynolds Number was varied from 1,500 to 9,000 by increasing the injection velocity. In these photographs, and in most of the others taken of injections into a vacuum, the nature of the flow seems to be controlled by the Reynolds Number, appearing to be laminar at values below the critical and turbulent above it.

The disintegration of the fuel jets in vacuum was much slower than in air. Sheets of fuel were thrown out from the higher velocity jets, and these later split into parts and were then drawn up into relatively large drops by the force of surface tension. In no case were any extremely fine drops formed in a vacuum, such as were observed when fuel was injected into air.

PHOTOMICROGRAPHS AT VARIOUS DISTANCES FROM THE NOZZLE

The progressive effect of the various forces acting on the fuel jet may be shown quite distinctly by photographing a jet at increasing distances from the nozzle, other conditions being kept constant. The photomicrographs in Figure 9 show the disintegration of a low-velocity jet at various stages of the process. The jet issuing from the orifice contains slight irregularities, which may be caused by fuel turbulence or by vibrations of the nozzle. These irregularities are accentuated by the action of the air until the jet consists of many irregular parts, which are then drawn out into ligaments by further action of the air, and the ligaments collapse to form drops. Here, at low velocity, are found in modified forms the types of jet disintegration previously described.

Photomicrographs of a high-velocity spray at different distances from the nozzle are shown in Figure 10. In this case, the relative air velocity is high enough to draw ligaments away from the jet as soon as it has been slightly ruffled.

In Figure 11, the velocity of the jet was about the same as that in Figure 10, but the viscosity of the fuel was 0.102 poise instead of 0.022. As was expected from the observations of other investigators, jets of this fuel did not disintegrate as quickly as jets of the less viscous fuel. Wavelike disturbances were very prominent with the more viscous fuel, and the ligaments were long, and slow to collapse into drops.

It is apparent from these photomicrographs that the disintegration of a jet is a progressive affair; as the distance from the nozzle increases so does the degree of disintegration, until the relative velocity of the fuel and air has become so low that interaction no longer takes place.

EFFECT OF AIR DENSITY

If the theory of atomization by ligament formation holds, there will be little tendency toward the formation of extremely fine drops when sprays are injected into a vacuum. The photomicrographs show that although there is sometimes considerable disintegration of fuel jets injected into a vacuum, in all such cases the jet is merely broken up into relatively large parts, or extended into wide sheets, and the drops are always larger than in sprays injected into air. (See figs. 3 and 12). As the air density is increased (fig. 12) the degree of disintegration of the jet at a given distance from the nozzle becomes greater, and the sizes of the fuel particles are apparently reduced.

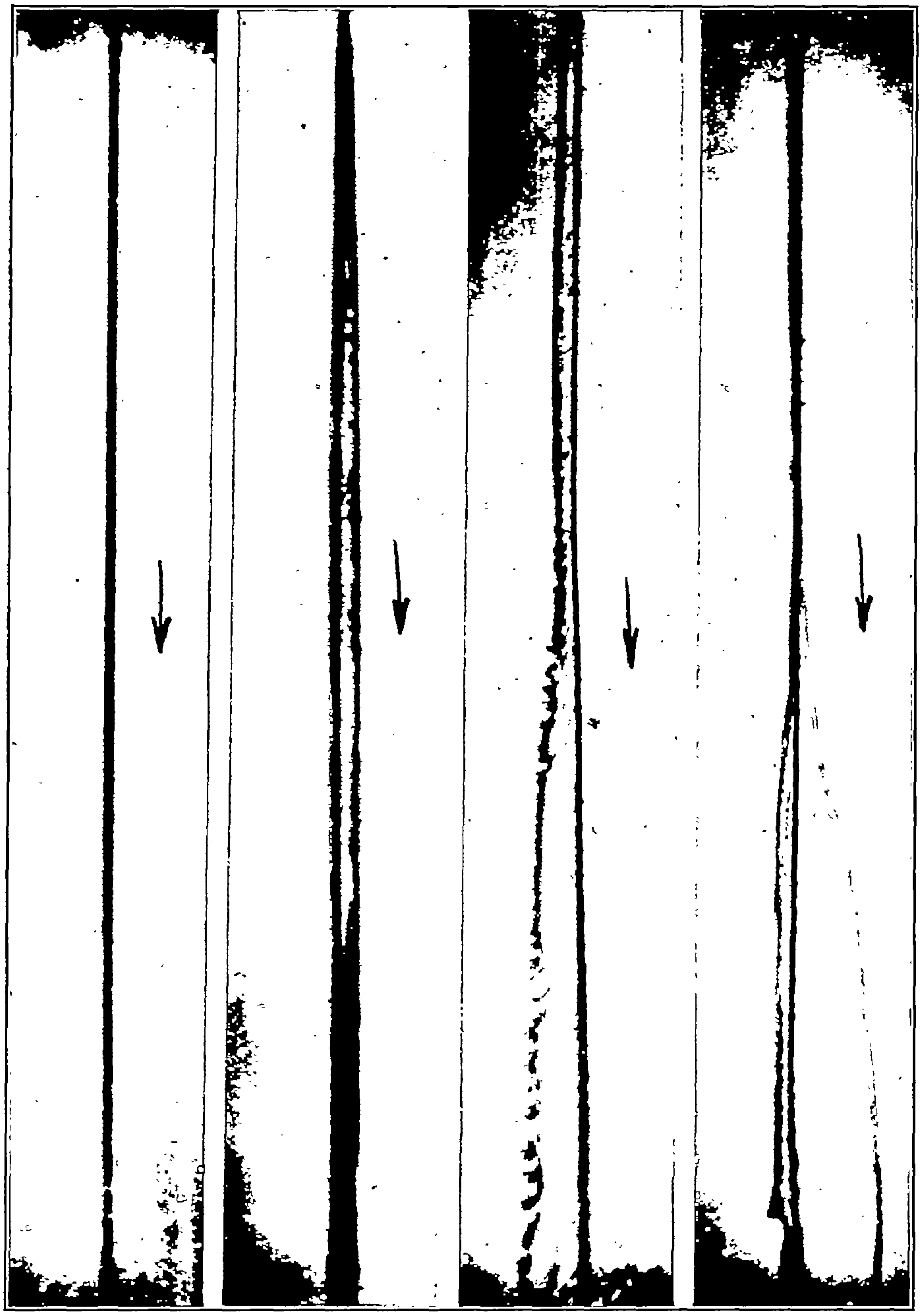
Injection pressure, 250 lb./sq. in.
Orifice diameter, 0.014 inch.
Distance from nozzle, 5 inches.
Fuel viscosity, 0.022 poise at 22° C.

Injection pressure, 550 lb./sq. in.
Orifice diameter, 0.020 inch.
Distance from nozzle, 5 inches.
Fuel viscosity, 0.022 poise at 22° C.

Injection pressure, 120 lb./sq. in.
Orifice diameter, 0.020 inch.
Distance from nozzle, 7.5 inches.
Fuel viscosity, 0.022 poise at 22° C.

Injection pressure, 700 lb./sq. in.
Orifice diameter, 0.020 inch.
Distance from nozzle, 1.5 inches.
Fuel viscosity, 0.102 poise at 22° C.

FIGURE 6.—Photomicrographs of fuel sprays showing the formation and collapse of ligaments, × 10. All sprays continuous, injected into air at atmospheric density

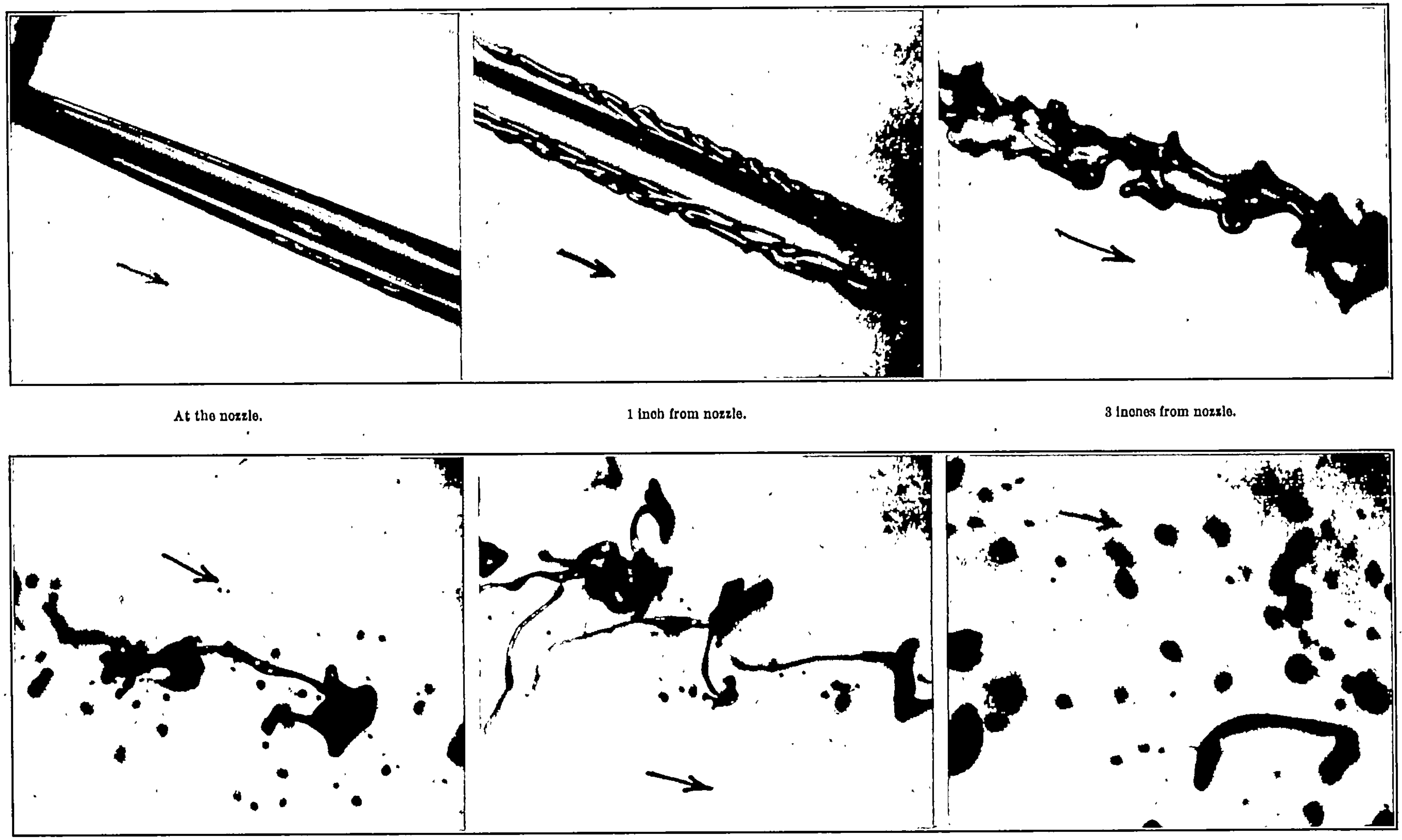


R. N.=1,500 R. N.=2,400 R. N.=2,600 R. N.=3,000

FIGURE 7.—Fuel jets at various Reynolds Numbers, in vacuum, × 2.5. Orifice diameter, 0.020 inch; air density, 0.0013 atmosphere (pressure=1 mm Hg, absolute); fuel viscosity, 0.102 poise at 22° C.; photographs taken just beyond the orifice

R. N.=3,500 R. N.=5,000 R. N.=7,000 R. N.=9,000

FIGURE 8.—Fuel jets at various Reynolds Numbers, in vacuum, × 2.5. Orifice diameter, 0.020 inch; air density, 0.0013 atmosphere (pressure=1 mm Hg, absolute); fuel viscosity, 0.102 poise at 22° C.; photographs taken just beyond the orifice



At the nozzle. 1 inch from nozzle. 3 inches from nozzle.

5 inches from nozzle. 7.5 inches from nozzle. 10 inches from nozzle.

FIGURE 9.—Photomicrographs of a low-velocity fuel jet at different distances from the nozzle, × 10. Injection pressure, 100 pounds per square inch; orifice diameter, 0.020 inch; air density, 1 atmosphere

The 2.5-power photographs in Figure 13 show the general effect of increasing the air density. The effective injection pressure in this case was maintained at 250 pounds per square inch above the chamber pressure, and even at this low injection pressure the cloud of fine drops in the envelope becomes very dense when the chamber-air density reaches values corresponding to those in compression-ignition engines at the time of fuel injection.

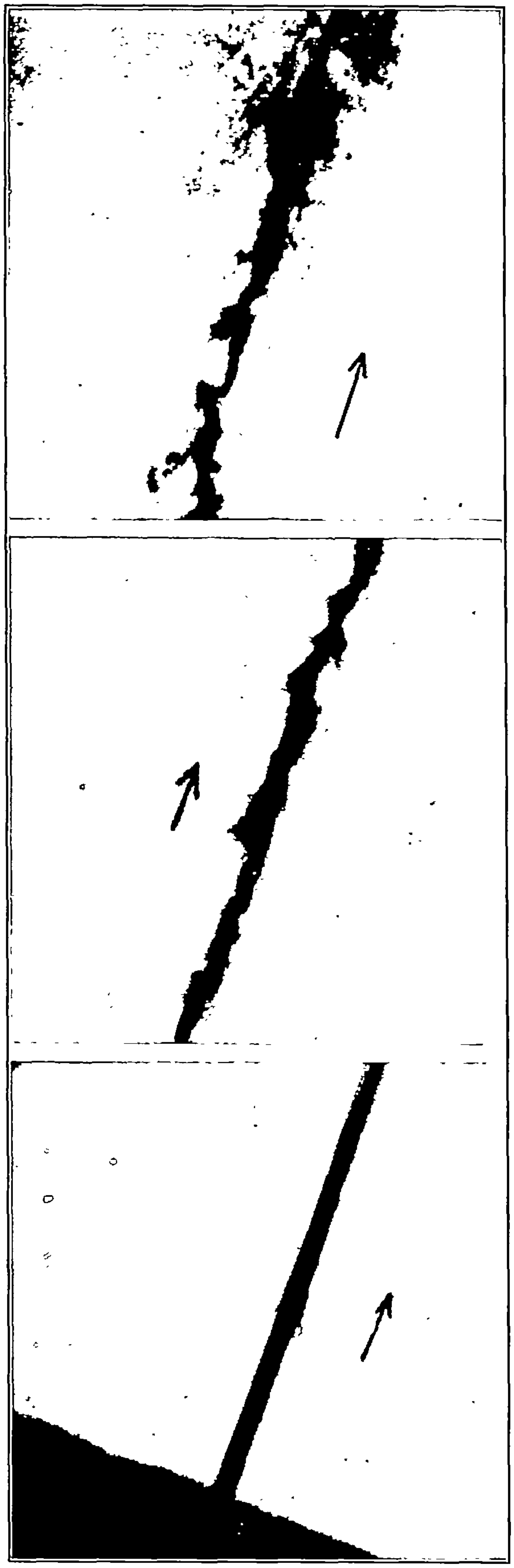
An examination of the photomicrographs taken at different air densities and at different distances from the nozzle, shows that, at a given injection pressure and distance from the nozzle, an increase in air density causes a very decided increase in the degree of disintegration of a jet. Substantially the same results may be obtained, however, by keeping the air density constant and increasing the distance from the nozzle. Thus it is seen that the disintegrating process is not completed immediately, but continues as long as the fuel retains enough velocity for the air to act upon it. In dense air, the process is more quickly carried to the limits obtainable with the jet velocity being used, but in air at low density the jet loses velocity more slowly and travels farther, and the final effect is the same, as shown in reference 10.

EFFECT OF THE CONDITION AND DIMENSIONS OF NOZZLE ORIFICES

It is a well-known fact that fuel jets from large orifices penetrate farther than jets from small orifices. In air whose density is atmospheric or greater, air forces predominate in the disintegration of the jet, so that small jets with their high surface/volume ratio are disintegrated sooner than large jets. Most of the photomicrographs showed this faster disintegration of small jets, other conditions being the same. As deceleration of the jet increases with its degree of disintegration, the reason for the greater penetrating power of large jets is apparent.

As will be noted when inspecting the various photographs of sprays in a vacuum, different nozzles may give greatly different dispersions at low air densities. As this difference in dispersion decreases rapidly with increasing air density, it is of little importance with respect to compression-ignition engines. In fuel-injection spark-ignition engines requiring injection during the intake stroke or early in the compression stroke, the air density is low enough for this change in dispersion to be effective.

Figure 12 showed the effect of air density on the dispersion of sprays from two nozzles, each having an orifice diameter of 0.008 inch but with different orifice lengths. In this case the spray from the orifice having a length/diameter ratio of 2.5 was more widely dispersed than that from the orifice having a ratio of 0.5. When two nozzles having orifice diameters of

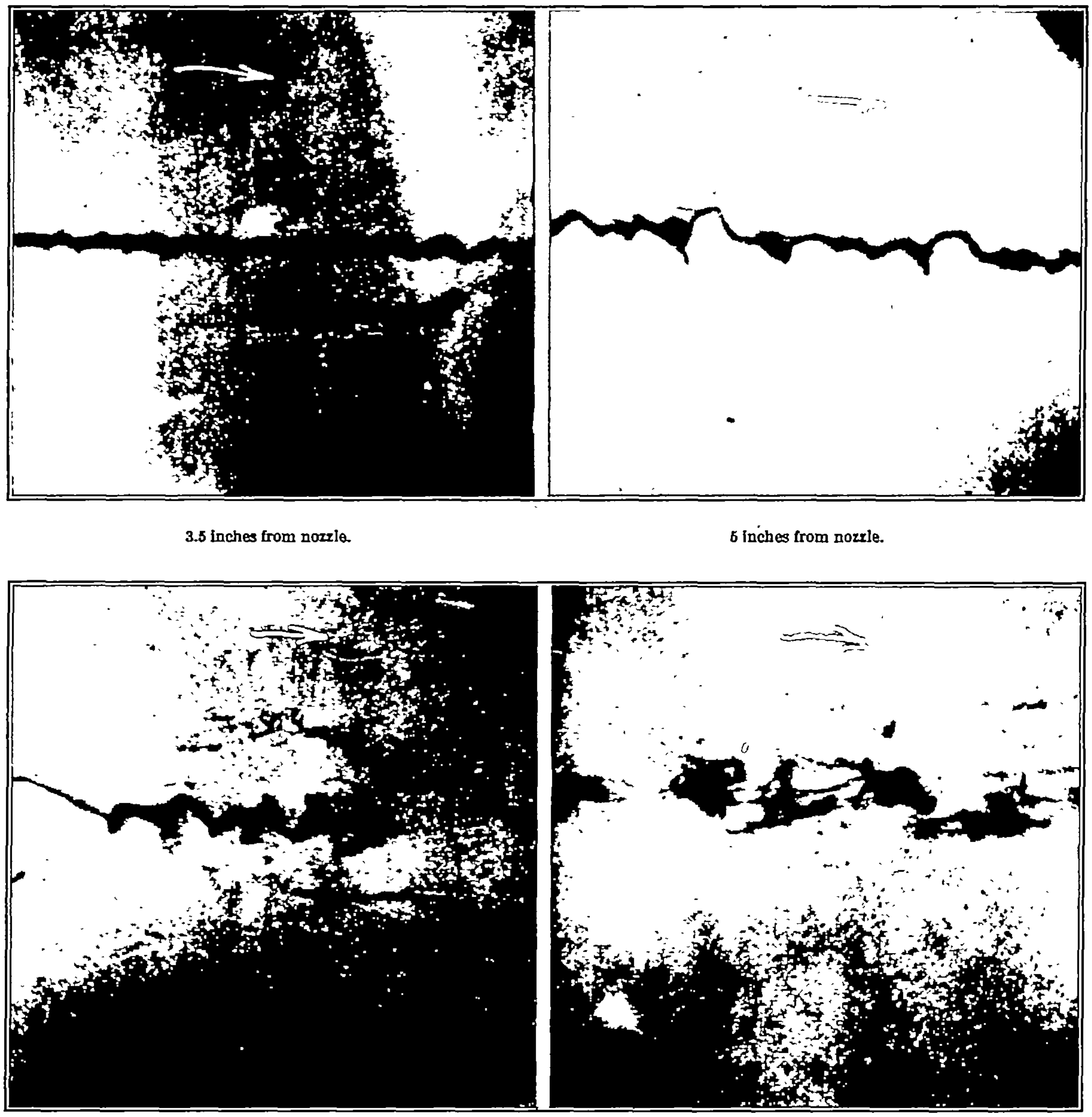


5 inches from nozzle.

2 inches from nozzle.

At the nozzle.

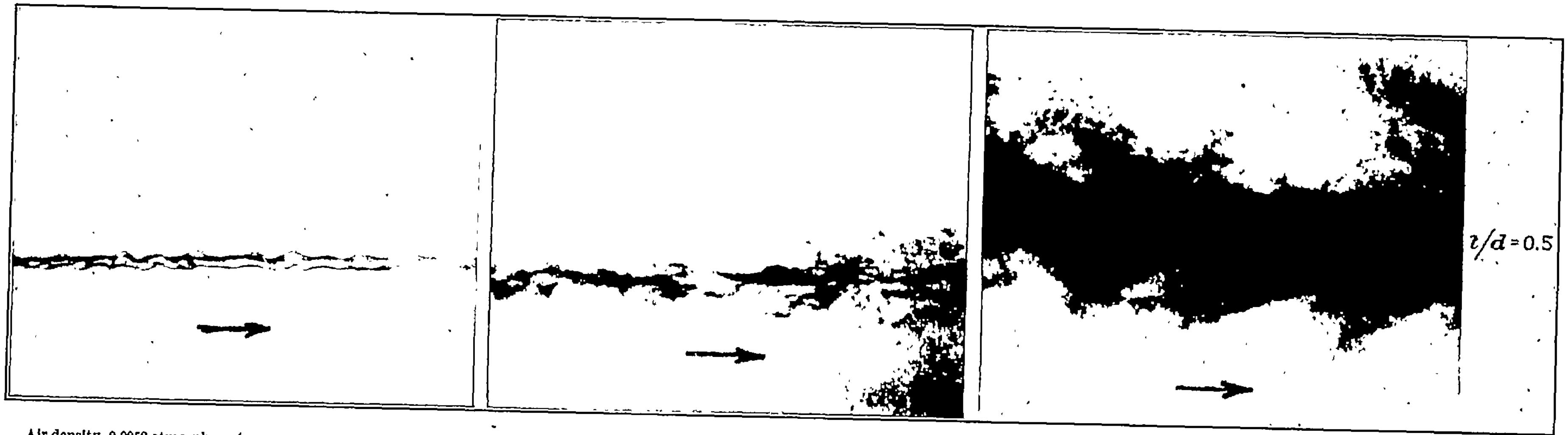
FIGURE 10.—Photomicrographs of a high-velocity fuel jet at different distances from the nozzle, × 10. Injection pressure, 1,000 pounds per square inch; orifice diameter, 0.014 inch; air density, 1 atmosphere



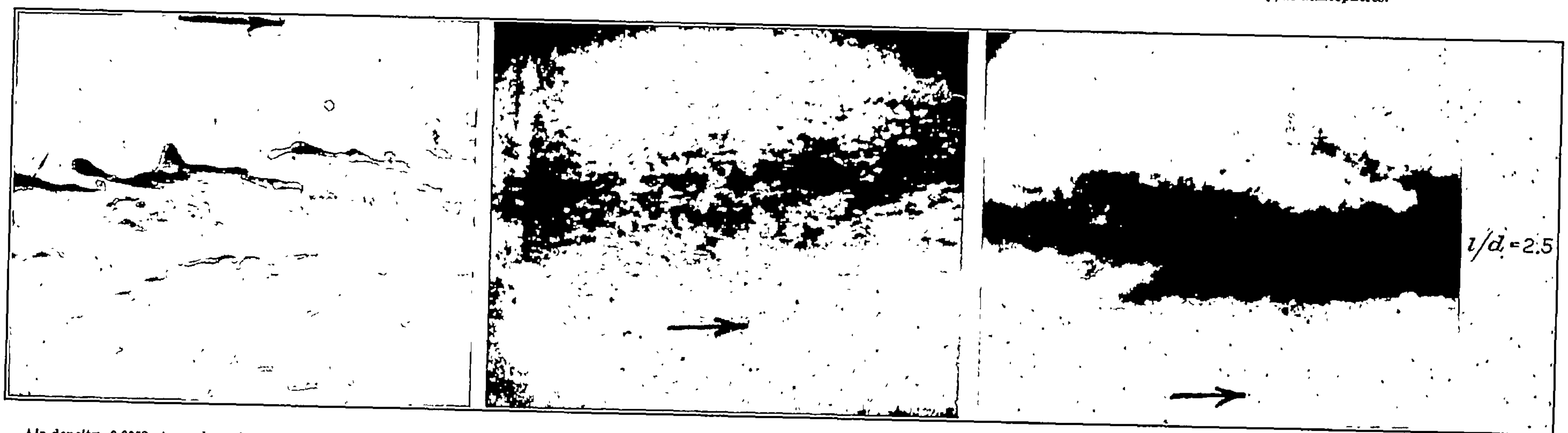
3.5 inches from nozzle. 5 inches from nozzle.

5.5 inches from nozzle. 6 inches from nozzle.

FIGURE 11.—Jet disintegration at different distances from the nozzle, × 10. Injection pressure, 1,000 pounds per square inch; orifice diameter, 0.008 inch; air density, 1 atmosphere; fuel viscosity, 0.102 poise at 22° C.



Air density, 0.0052 atmosphere (pressure=4 mm Hg, absolute). Air density, 1 atmosphere. Air density, 13 atmospheres.



Air density, 0.0052 atmosphere (pressure=4 mm Hg, absolute). Air density, 1 atmosphere. Air density, 13 atmospheres.

FIGURE 12.—Effect of air density on fuel jets from nozzles having orifice length/diameter ratios of 0.5 and 2.5, × 10. Injection pressure, 1,000 pounds per square inch; orifice diameters, 0.008 inch; distance from nozzle, 1.5 inches

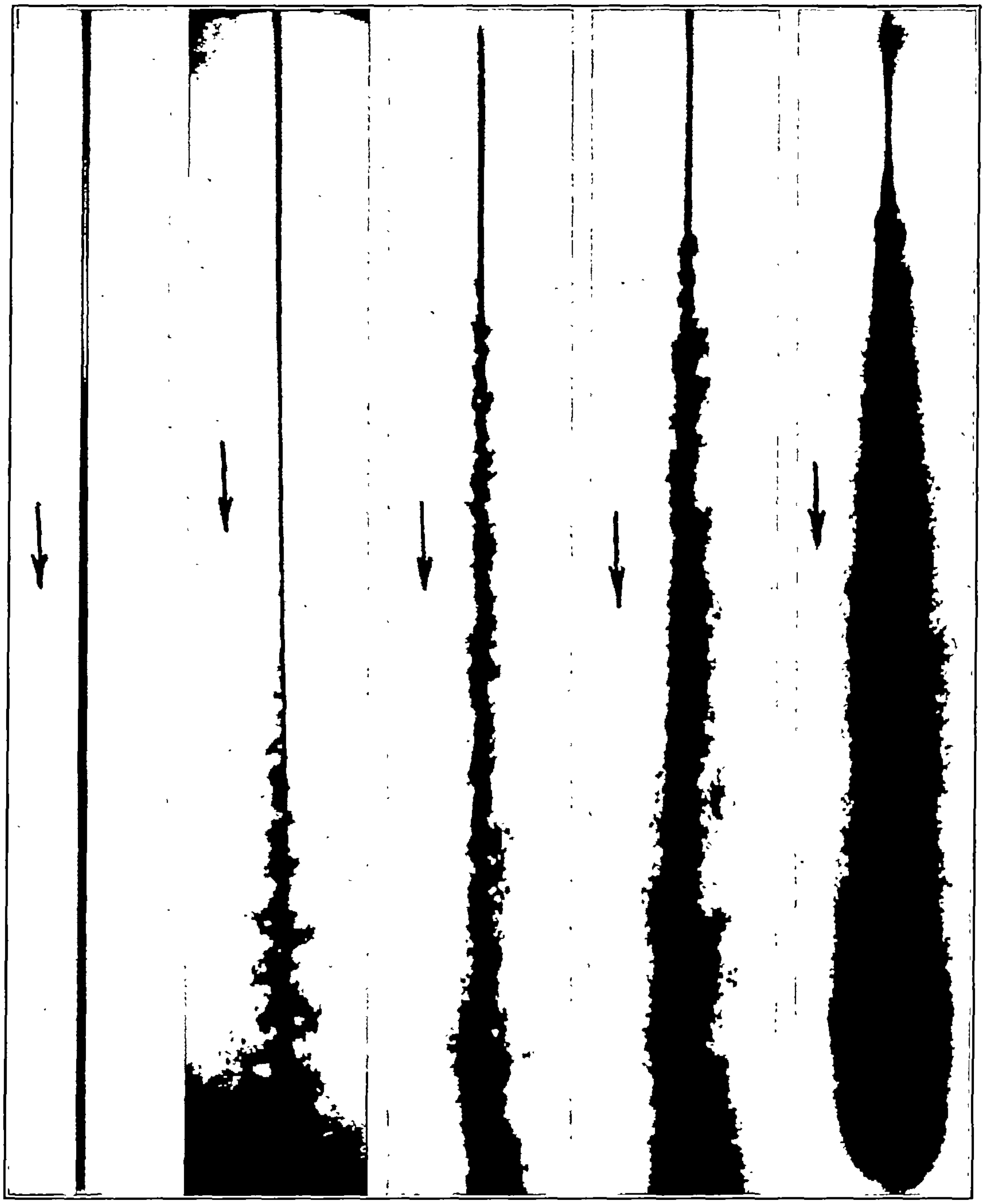


FIGURE 13.—Effect of air density on fuel jets, × 2.5. Effective injection pressure, 250 pounds per square inch; orifice diameter, 0.020 inch; fuel viscosity, 0.130 poise at 22° C.

Air densities:

(a) 0.0013 atmosphere. (b) 1 atmosphere. (c) 4.4 atmospheres. (d) 7.8 atmospheres. (e) 14 5 atmospheres.

(a) (b) (c)

FIGURE 14.—Jets from orifices having the same dimensions, in vacuum. × 2.5. Injection pressure, 3,000 pounds per square inch; orifices, 0.014 inch in diameter and 0.028 inch long; air density, 0.0013 atmosphere (pressure=1 mm Hg, absolute)

Nozzles:
(a) straight hole in thin steel plate. (b) conventional nozzle, polished. (c) conventional nozzle, unpolished.

0.014 inch and lengths of 0.006 and 0.028 inch were tried, it was found that the shorter orifice produced the greater dispersion. Four nozzles having orifice diameters of 0.020 inch and lengths of 0.010, 0.040, 0.100, and 0.200 inch were also tried. In this case the 0.040-inch-long orifice produced the widest spray. Nozzles similar to the ones used in the present experiments were used by Gelalles in his measurements of spray-tip penetration. (Reference 11.) He found that the spray-tip penetration was least with orifice length/diameter ratios of 2 or 3, and greatest with a ratio of about 6.

Photographs taken of jets from three nozzles having identical orifice lengths and diameters, but differing in other respects, are shown in Figure 14. The nozzle for Figure 14 (a) was a straight hole in the center of a steel disk. The nozzles for (b) and (c) were of the type shown in Figure 2, the difference being that for (b) the orifice was polished after it was drilled out, but for (c) the orifice was left rough.

Another example of the effect of small irregularities in the nozzle on spray dispersion is shown in Figure 15. Photograph (a) shows a spray from a slightly corroded nozzle, and (b) shows a spray from the same nozzle after it had been carefully polished.

(a) Orifice pitted by rust. (b) Orifice polished.

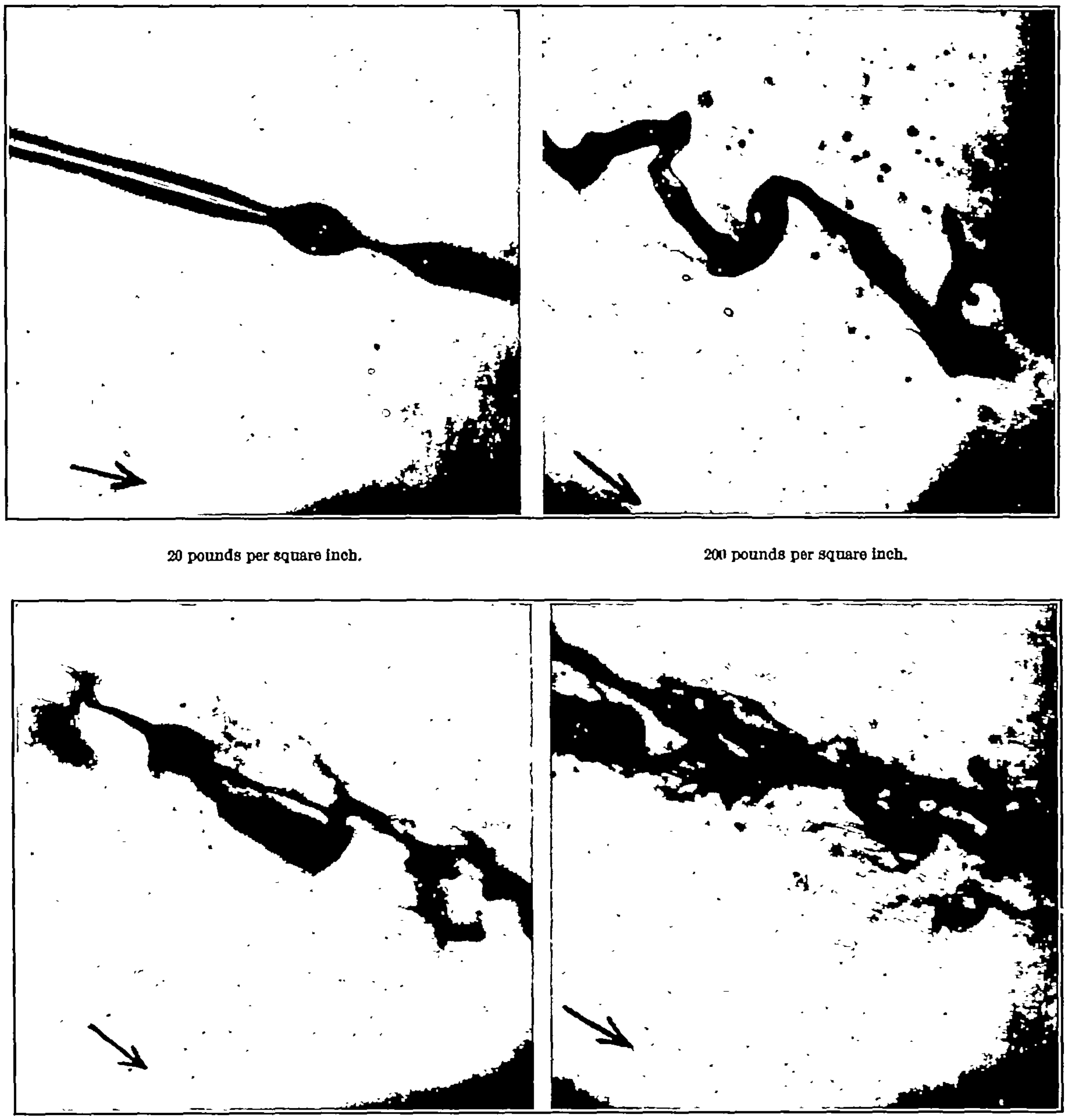
FIGURE 15.—Change in dispersion when disturbing influences are present in the orifice, × 10. Injection pressure, 1,000 pounds per square inch; orifice diameter, 0.008 inch; air density, 0.0053 atmosphere (pressure=4 mm Hg, absolute); distance from nozzle, 3 inches

EFFECT OF INJECTION VELOCITY

The effect of injection velocity on the disintegration of fuel jets is shown by the photomicrographs of Figures 16, 17, and 18. As the injection velocity is increased, the disintegrating forces which result from air action and from fuel turbulence increase. At very low injection velocities, when these forces are slight, the entire jet may be seen in the various characteristic forms of jet disintegration. At higher injection velocities the jet issues from the orifice in a turbulent condition, and the irregular surface is accentuated by air action. The fuel is divided into smaller and smaller parts until the air forces can no longer overcome the resisting forces due to the surface tension and viscosity of the fuel. These smallest parts then collapse to form drops. Ligaments may be drawn directly from the unbroken column soon after it has been ruffled, but the majority are formed after the jet has been disintegrated into parts. At very high velocities the ligaments are so small that most of them will probably not be visible in the photomicrographs when they are reproduced for publication. Ligaments have been observed on the original negatives of sprays injected into air at a density of one atmosphere at injection pressures as high as 4,000 pounds per square inch.

HIGH DISPERSION NOZZLES

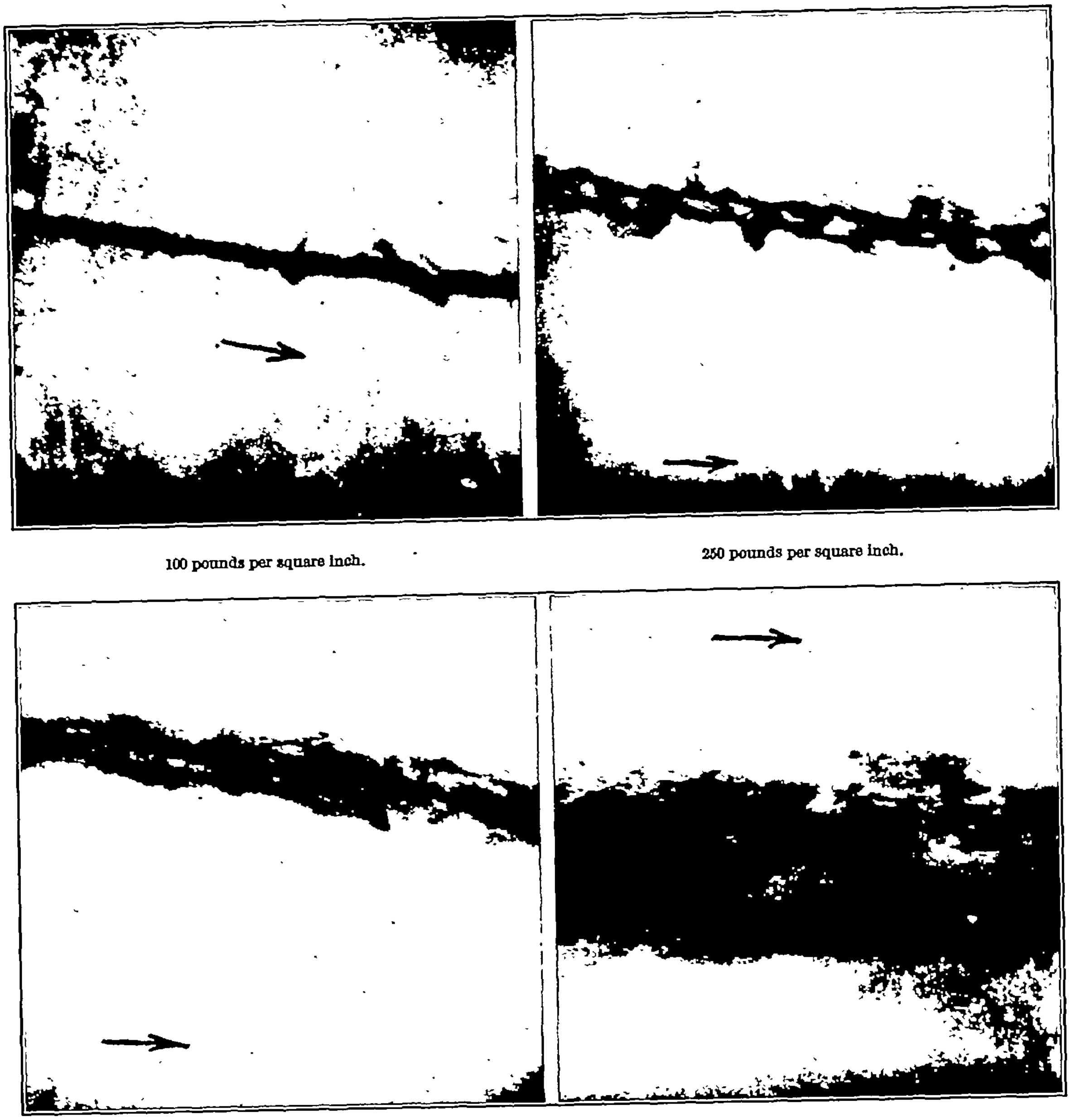
Nozzles intended to give great dispersion are generally designed to produce a jet of fuel that has as large a surface as possible exposed to the action of the air. Flow conditions in such nozzles usually produce considerable turbulence, and the combination of turbulence and large surface exposed to the air causes very rapid jet disintegration. Figures 19 and 20 show the flow conditions at the exit of some nozzles of this type. For clearness the injection velocities were kept below 130 feet per second and the sprays injected into the atmosphere. Figure 19(a) shows the pronounced whirling of the fuel as it leaves a nozzle equipped with a helically grooved stem. Figure 19(b)



20 pounds per square inch. 200 pounds per square inch.

300 pounds per square inch. 900 pounds per square inch.

FIGURE 16.—Effect of injection pressure on jet disintegration, × 10. Orifice diameter, 0.020 inch; air density, 1 atmosphere; distance from nozzle, 4.75 inches



100 pounds per square inch.

250 pounds per square inch.

1,000 pounds per square inch.

4,000 pounds per square inch.

FIGURE 17.—Effect of injection pressure on jet disintegration, × 10. Orifice diameter, 0.008 inch; air density, 1 atmosphere; distance from nozzle, 2.5 inches

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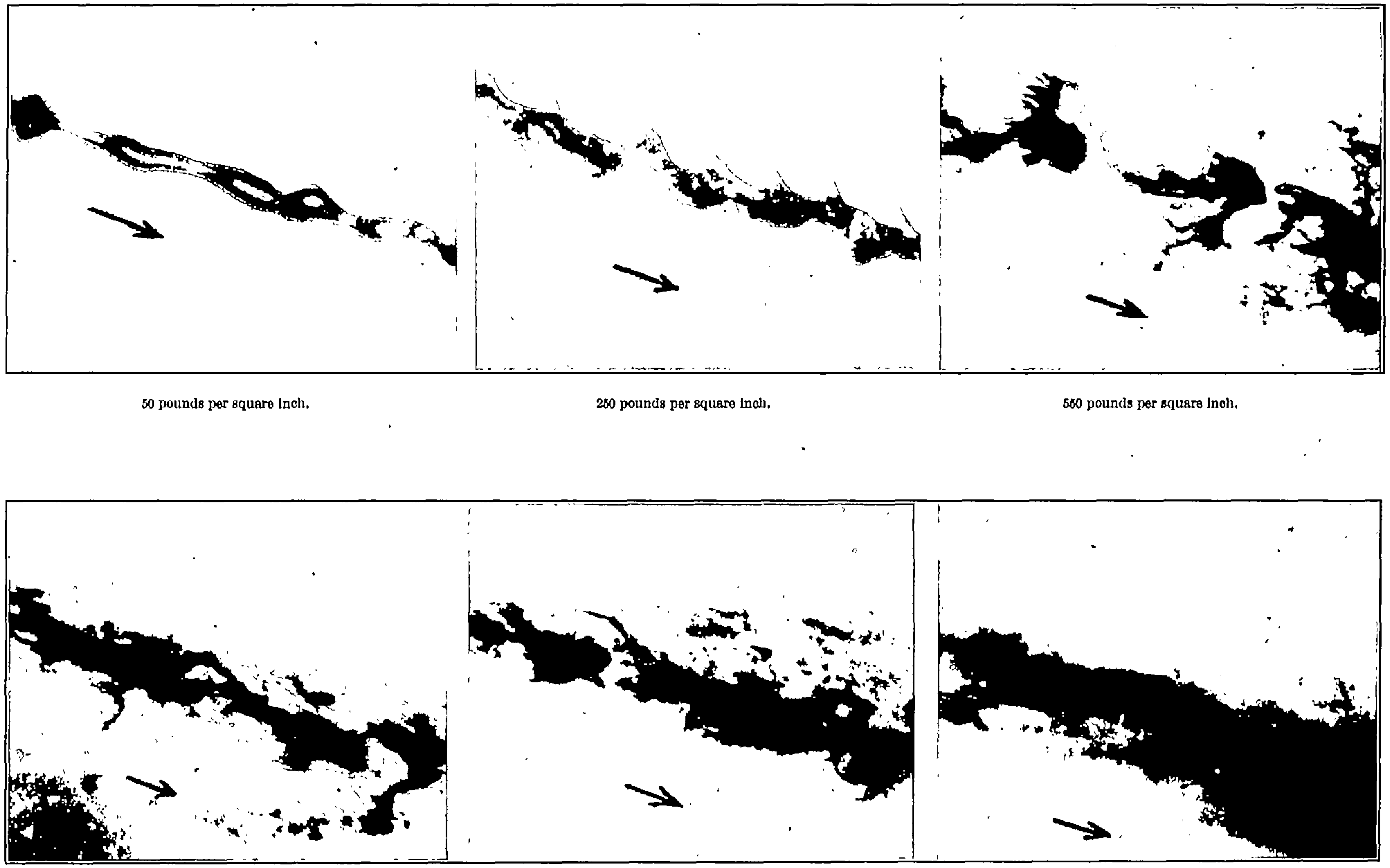
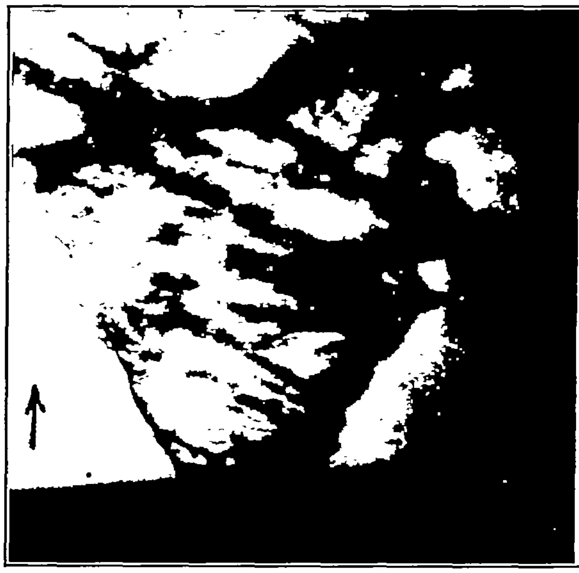


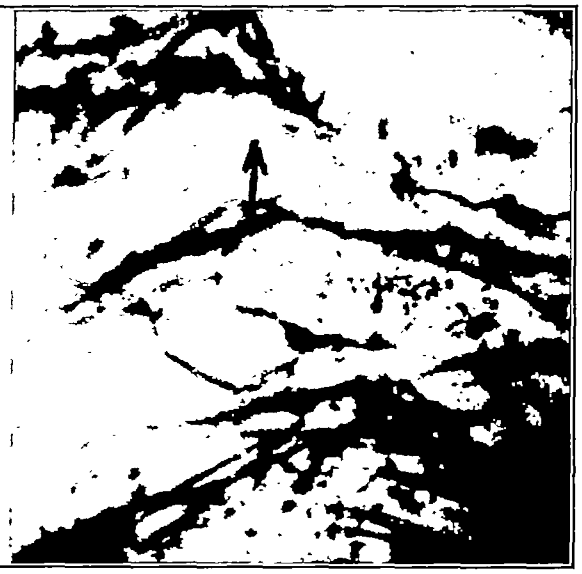
50 pounds per square inch. 250 pounds per square inch. 550 pounds per square inch.

1,000 pounds per square inch. 1,500 pounds per square inch. 2,000 pounds per square inch.

FIGURE 18.—Effect of injection pressure on jet disintegration, × 10. Orifice diameter, 0.020 inch; air density, 1 atmosphere; distance from nozzle, 5 inches



(a) Centrifugal-type spray.



(b) Spray from impinging-jets nozzle.

(c) Slit nozzle.

(d) Slit nozzle.

FIGURE 19.—Flow conditions at exit of some high-dispersion nozzles, × 10. Injection pressure, 100 pounds per square inch or less; air density, 1 atmosphere

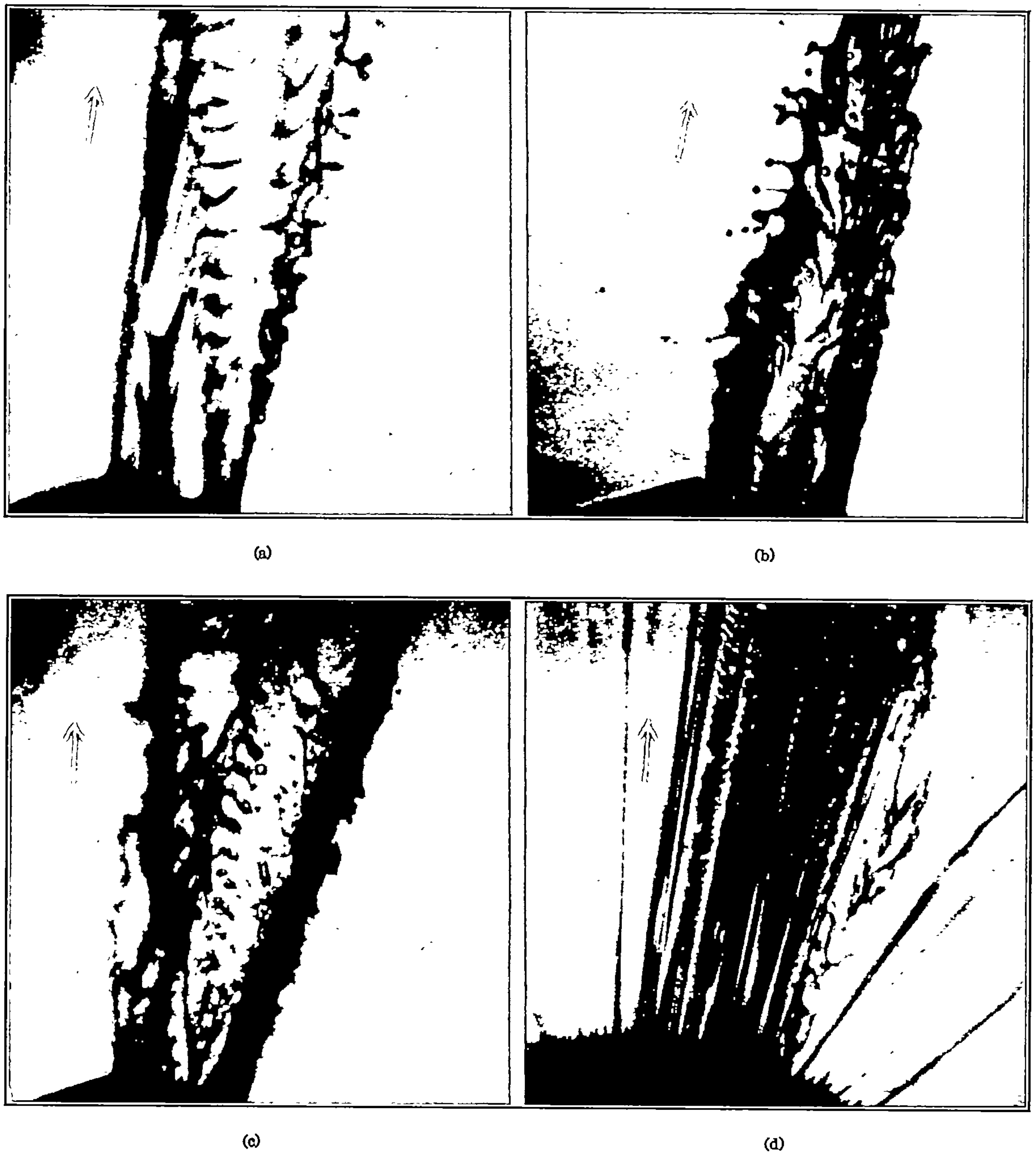


FIGURE 20.—Flow conditions at exit of some high-dispersion nozzles, × 10. Injection pressure, 100 pounds per square inch or less; air density, 1 atmosphere; all sprays from slit nozzles

Gasoline. Water. Ethyl alcohol.

Diesel fuel No. 1. Diesel fuel No. 2. Lubricating oil.

FIGURE 21.—Jets of various liquids, × 10. Injection pressure, 1,500 pounds per square inch; orifice diameter, 0.020 inch; air density, 1 atmosphere; distance from nozzle, 5 inches

shows the flat side of the spray from an impinging-jets nozzle, just beyond the point of impingement. Figure 19(c) shows the flat side of a sheet of fuel injected from a slit orifice in a hemispherically shaped nozzle. The irregular waves were probably the result of air forces. In Figure 19(d) the flat side of a sheet of fuel from a rectangular slit is shown. The regularity of the waves and the fact that they seem to possess their full amplitude as they leave the nozzle suggest that they are the result of nozzle vibrations.

The low-velocity jets shown in Figure 20 were all from slit nozzles. The turbulence of the flow shown in photographs (a) and (b) was of such a nature that a few large drops were thrown off at right angles to the main jet. The peculiar flow conditions shown in (c) were caused by a slight obstruction in the slit orifice. Photograph (d) shows examples of laminar flow, forced vibrations, and turbulent flow in different parts of a fan-shaped sheet of fuel.

EFFECT OF DIFFERENT LIQUIDS

Sass (reference 12) took 10-power photomicrographs of sprays of fuels having different viscosities and concluded that the atomization improved as the viscosity was decreased.

A number of photomicrographs were taken at this laboratory using different liquids to determine qualitatively the effects of viscosity and surface tension on spray formation. For convenience the viscosities and surface tensions of the various liquids are listed in Table I. All values were determined at temperatures as near as possible to those prevailing in the laboratory at the time the photomicrographs were taken.

TABLE I

PROPERTIES OF LIQUIDS USED

[Temperature, 22° C.; pressure, atmospheric]

Liquid	Viscosity, poises	Surface tension, dynes per cm
Gasoline	0.0042	21
Water	.0096	68
Ethyl alcohol	.0115	24
Diesel fuel No. 1	.022	27
Diesel fuel No. 2	.102	28
Lubricating oil	3.07	31

Representative photographs taken at 1,500 pounds per square inch injection pressure were selected and are shown in Figure 21. At higher injection pressures the differences in behavior become more evident, but at such high pressures and under these particular conditions the photographs are blurred and unsuitable for reproduction.

Examination of the photomicrographs of Figure 21 and the values given in Table I shows that for any one set of conditions the degree of disintegration of the jet decreases as the viscosity is increased. In the case of water, a decided effect of the increased surface tension in reducing the degree of jet disintegration is noticeable. However, for such differences in surface tension as are found among the various fuels the effect is negligible.

ATOMIZATION MEASUREMENTS

Most of the photomicrographs were entirely unsuitable for quantitative measurements of the fineness of the atomization. In the atmosphere the atomization process was usually not completed in the region photographed, and in dense air the photomicrographs

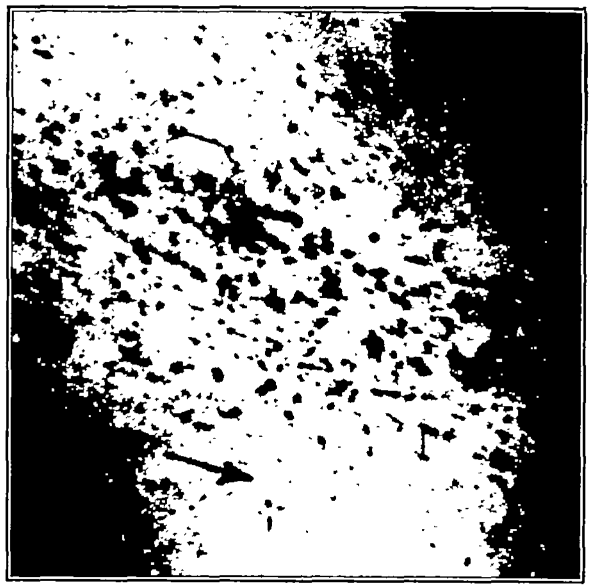


FIGURE 22.—Photomicrograph used to measure drop sizes for the Diesel fuel No. 1 curve of Figure 24

were not clear. In a few cases, however, it was possible to measure the sizes of the fuel particles from the photomicrographs. An example of such a photomicrograph is shown in Figure 22. Only a very small part of the spray was included in the field of the microscope, and many of the fuel particles were irregular or out of focus, so that the results may not be truly representative of the entire spray. The atomization measurements are included in this report because they support some of the conclusions reached from a study of all the photomicrographs.

In Figures 23 to 25 the ordinates of the curves show what percentage of the fuel volume was broken up into drops having diameters between zero and the value of the abscissa. In Figure 23 curves obtained by measuring photomicrographs of sprays injected into the atmosphere from an orifice 0.008 inch in diameter and 0.020 inch long are compared with curves for carburetor atomization (from Scheubel, reference 9) and with curves for fuel injections into dense air (data from Lee, reference 10). Each curve is identified by the relative velocity between the fuel and the air. For the carburetor sprays this is the air velocity at the Venturi throat, and for the injected sprays it is the initial fuel-jet velocity. A strict comparison of these different sets of curves is impossible because of the different fuels, nozzles, and air densities used, but the fact that the curves arrange themselves according to their relative fuel-air velocities shows that it is this factor which predominates. Moreover, the close agreement between Scheubel's curves for alcohol and those obtained from photomicrographs of alcohol sprays injected into the atmosphere supports Castleman's conclusion that the atomization process in injected sprays is the same as that in carburetors.

The curves in Figure 24 give atomization data for four different liquids at low fuel-air velocities. They supplement the conclusions derived from a study of the photomicrographs as to the effects of the surface tension and viscosity of the fuel on jet disintegration. At these low injection velocities the atomization of Diesel fuel No. 2 and lubricating oil had not begun at 5 inches from the nozzle, the distance at which all the atomization measurements were made.

As a supplement to the above experiments, atomization measurements were made with Diesel fuels Nos. 1 and 2 at an injection velocity of 765 feet per second (pressure=4,000 pounds per square inch) and an air density of 1.01 pounds per cubic foot. The sprays were caught on smoked-glass plates and the impressions made there by the fuel drops were counted and measured. For a complete description of this method, see reference 10. The results of these measurements

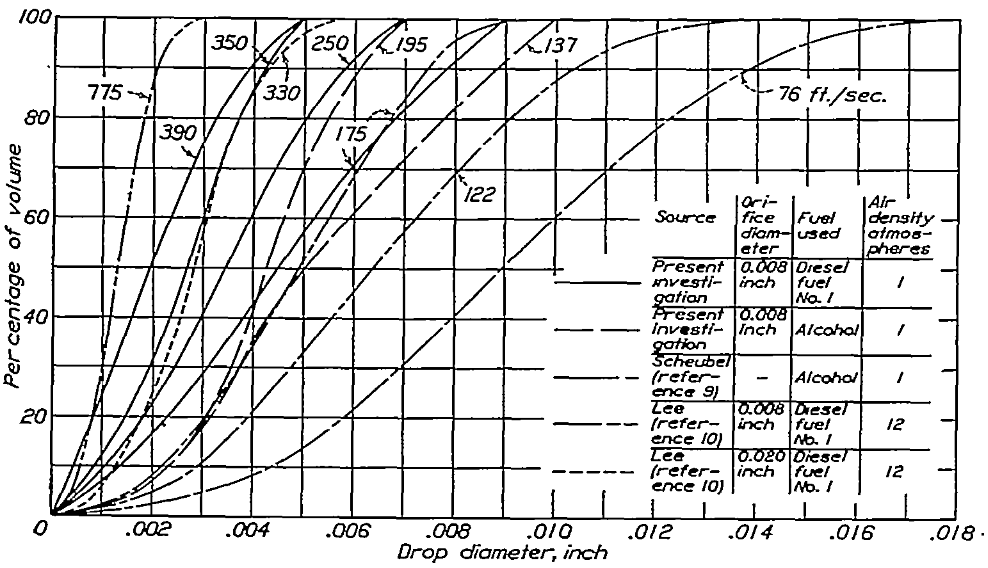


FIGURE 23.—Comparison of atomization data from different sources

are shown in Figure 25. The atomization was finer for the less viscous fuel, but the effect of fuel viscosity was less pronounced under these conditions than it was at low injection velocities and low air densities.

CONCLUSIONS

This photomicrographic study of fuel sprays has shown that the fuel leaves the nozzle as an unbroken column, but is quickly disintegrated into many irregular parts by a combination of fuel-stream turbulence and forces resulting from the relative motion between the fuel and the air. Atomization is accomplished by

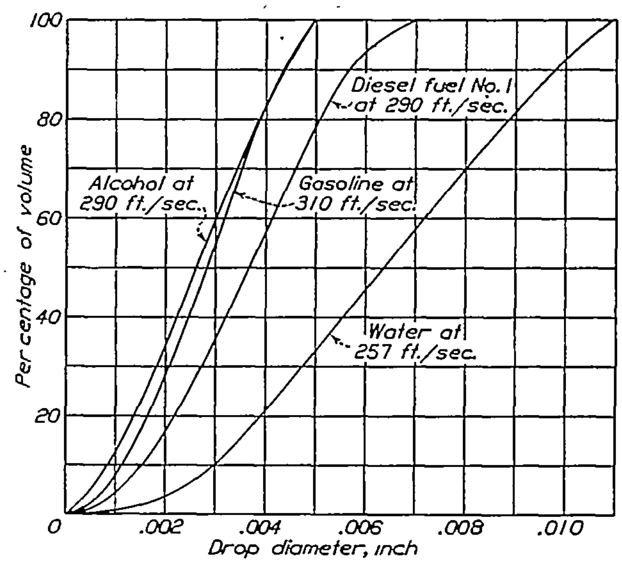


FIGURE 24.—Atomization data for different liquids. Orifice diameter, 0.008 inch; air density, 1 atmosphere

air acting upon the fuel column and the detached parts, tearing off fine, irregular threads or ligaments, which subsequently collapse into drops because of the surface tension of the fuel. The observations of

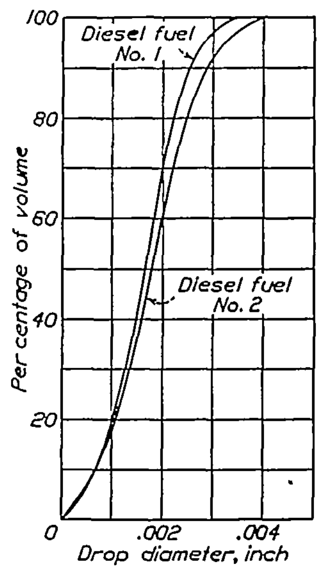


FIGURE 25.—Effect of fuel viscosity on the fineness of the atomization. Injection pressure, 4,000 pounds per square inch (initial jet velocity about 785 feet per second); orifice diameter, 0.020 inch; air density, 13 atmospheres.

ligament formation and the results of drop size measurements, within the range investigated, support the conclusion of Dr. R. A. Castleman, jr., that the atomization process in injected sprays is the same as that in carburetors.

When other variables are held constant, the degree of disintegration of the jet:

(a) Increases with distance from the nozzle, until the disintegrating forces due to the relative velocity between the air and the fuel are no longer sufficient to overcome the resisting forces due to the surface tension and viscosity of the fuel.

(*b*) Increases with increase of air density.

(*c*) Increases with increase of jet velocity.

(*d*) Decreases with increase of orifice diameter.

(*e*) Decreases with increase of fuel viscosity.

(*f*) Decreases with increase of fuel surface tension.

(*g*) Increases with increase of fuel turbulence. Fuel turbulence accelerates the disintegration of the fuel jet by ruffling its surface close to the orifice, but it has relatively little disintegrating force in itself.

At atmospheric and subatmospheric air densities there may be wide differences in the dispersion of sprays from geometrically similar nozzles, because of different degrees of turbulence caused by slight irregularities in the nozzles. This difference is also shown between the early and late parts of sprays from nozzles used with automatic injection valves. At air densities corresponding to those in compression-ignition engines at the time of fuel injection the differences are slight.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *December 15, 1932.*

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